A POSSIBLE INITIAL CONDITION FOR RED TIDES ON THE COAST OF FLORIDA

By

L. BASIL SLOBODKIN

Visiting Investigator at
Bingham Oceanographic Laboratory

ABSTRACT

It seems likely that the occurrence of a discrete mass of water, with a salinity lower than that of normal Gulf of Mexico surface water, is a necessary prerequisite for the occurrence of red tide off the Florida Coast.

On the basis of certain elementary assumptions, it has been shown by Kierstead and Slobodkin (1953) that there is a minimum critical size for a water mass physiologically suitable for the growth of a phytoplankton population which will permit an increase in the concentration of organisms. If the rate of increase of the phytoplankton is given by

$$\frac{dN}{dt} = KN, \tag{1}$$

where N is the total number of organisms in the water mass, then the size of the critical water mass is given by

$$L_c = \pi \sqrt{\frac{D}{K}} \tag{2}$$

in a linear model, where D is the rate of diffusion and L_c is the length of the water mass. For any length less than L_c, the organisms will not increase in concentration.

In a circular model the relation is given by

$$R_c = 2.4048 \sqrt{\frac{D}{K}}, \tag{3}$$

where R_c is the radius of the water mass. The order of magnitude of the relation remains unchanged by geometric assumptions.

This relationship is not of particular significance if the phytoplankton species in question is tolerant of a wide range of environmental conditions, but it is important if the physiological requirements and tolerance of the species are highly specialized. The dinoflagellates

responsible for red t
Brongersma-Sander:
culture techniques
Gymnodinium brevis
the Florida Coast (1
phytoplankton of th
It can be assumed,
these organisms are
their propagation ar

On *a priori* ground
chemical properties (
these organisms, sm
will be more commor
considered fixed at a
Therefore the possibi
of D in (2) and (3)
decreasing values of
coefficient of eddy di
promote the occurren
those that lower the

While the precise th
that diffusivity is red
density (Ichie and Ka
to current velocity
expected when densit
of small water masses
in a local area will pr
expected to show a lo
red tides may be coast
age. Examination of
during the period im
Coast confirms this ex

In compiling Table
recorded outbreak we
the stations with heav
of data, but in no case
and the point of initial
water mass moving fro

On June 2, 1952 red
30′ W Long. and 28°
Wildlife vessel ALASK
population of a red cil
closely related form (K

ID TIDES

r, with a salinity
ssary prerequisite

as been shown
nimum critical
e growth of a
se in the con-
)hytoplankton

(1)

nass, then the

(2)

, is the length
irganisms will

(3)

magnitude of
is.
f the phyto-
e of environ-
requirements
linoflagellates

responsible for red tide outbreaks (Gunter, et al., 1948; Galtsoff, 1948; Brongersma-Sanders, 1948) are not generally amenable to normal culture techniques (personal communication from Provasoli), and *Gymnodinium brevis*, the species responsible for the 1947 outbreak on the Florida Coast (Davis, 1947) is not normally found in the marine phytoplankton of the region (personal communication from Graham). It can be assumed, therefore, that the physiological requirements of these organisms are specialized and that water masses suitable for their propagation are not common.

On *a priori* grounds it seems reasonable to consider that, if peculiar chemical properties (as yet undefined) are required for propagation of these organisms, small masses of water with the required properties will be more common than large ones. The value of K in (1) can be considered fixed at a first approximation. L will probably be small. Therefore the possibility of a plankton bloom will depend on the value of D in (2) and (3). The likelihood of a bloom will increase with decreasing values of D. D can be considered to vary as A, the coefficient of eddy diffusivity (Riley, 1951), and the conditions which promote the occurrence of a bloom can be considered as identical with those that lower the value of A.

While the precise theory of diffusivity is still unknown, it is apparent that diffusivity is reduced at the junction of water masses of different density (Ichie and Katsumi, 1949) and that it is roughly proportional to current velocity (Riley, 1951). Therefore, red tides might be expected when density differences are liable to permit the persistence of small water masses. Admixture of nonsaline water with sea water in a local area will produce a mass of low density water which may be expected to show a low mixing rate at its boundaries. Therefore, the red tides may be coastal phenomena associated with heavy land drainage. Examination of the rainfall data of the U. S. Weather Bureau during the period immediately preceding red tides on the Florida Coast confirms this expectation (Table I).

In compiling Table I, weather stations in the region of the first recorded outbreak were examined. The values shown are those of the stations with heaviest rainfall. This involves arbitrary selection of data, but in no case does the distance between the weather station and the point of initial reported outbreak preclude the possibility of a water mass moving from one to the other without losing its integrity.

On June 2, 1952 red discoloration of the sea at approximately 84° 30′ W Long. and 28° 30′ N Lat. was found by the U. S. Fish and Wildlife vessel ALASKA. This discoloration was caused by a dense population of a red ciliate, probably *Mesodinium pulex* Noland or a closely related form (Kudo, 1947). The surface salinity at a hydro-

TABLE I(a). DATE AND LOCATION OF RED TIDE OFF THE FLORIDA COAST, AND ASSOCIATED RAINFALL

Year	Date of Initial Report	Location of Red Tide	Rainfall (inches), Month; Weather Station
1844	Unknown (Ingersoll, 1882)	Tampa Bay	15.79, August; Tampa
1854	Unknown (Ingersoll, 1882)	Tampa Bay	15.5, July; Tampa
1878	September (Jefferson, et al., 1878)	Florida Bay	9.40, August; 25.10, September; Miami
1880	August (Ingersoll, 1882)	Tampa Bay	6.40, July; 14.00, August; Tampa
1882	July 20 (Anonymous, 1882)	Mouth of Tampa Bay	5.28, June; 10.44, July; Tampa
1883	Reported by Brongersma-Sanders (1948) from Walker (1884). Reference to Walker's original paper shows that these authors refer to the same 1880 outbreak. Walker's paper was submitted for publication under date of December 21, 1880.		
1885	October (Glennan, 1886)	Egmont Key to Charlotte Harbor	10.64, September; 1.95, October; Tampa 13.68, September; Manatee
1908	Reported by Taylor (1917) as killing sponges, without any mention of dead fish. This is probably an outbreak of sponge blight rather than red tide (Smith, 1941).		
1916	October 3 (Taylor, 1917)	Boca Grande to San Carlos Bay	12.56, July; 8.22, August; 5.34, September; Fort Myers
1946*	November 20 (Gunter, et al., 1948)	Naples	9.23, September; 2.03, October; 9.69, November; Naples

In October 1946, Fort Meyers, Punta Gorda and the Everglades, Florida were flooded by unusual tides in the wake of a hurricane on October 7–8. Charlotte Harbor and part of the Everglades can be considered as having been thoroughly mixed with sea water, which drained into the Gulf of Mexico in considerable volume. November was warmer by 6.1° than any previous November on record (71.2° mean for Florida). October was 1.1° above normal and warmer than any October in five years for the state as a whole.

Year	Date of Initial Report	Location of Red Tide	Rainfall (inches), Month; Weather Station
1947*	March (Gunter, et al., 1948)	Florida Bay	10.37, March; Captiva 8.94, March; Fort Meyers Greatest March rainfall on record for state with exception of 1930
1947*†	June 20 (Gunter, et al., 1948)	Bonita Beach (South of Fort Myers)	6.47, May; 12.84, June; Fort Myers (2.69 inches fell after June 20) 3.34, May; 13.33, June; Punta Gorda (.04 inches fell after June 20)
1947*†	July 18 (Gunter, et al., 1948)	Venice to Sarasota	13.06, June; 11.44, July; Sarasota (7.64 inches after July 18) 18.25, July; Punta Gorda (12.72 after July 18) Floods in Okeechobee region during June and July
1952	October 25	Boca Grande and Southwest of Sanibel	12.35, September; 8.34, October; Fort Myers (none after October 25)

* All outbreaks marked with an asterisk are considered by Gunter, et al. (1948) as representing a single occurrence. Since discoloration and fish mortality disappeared between each of the listed dates, they are here considered as separate.

† The interval with no fish kills separating these two outbreaks is of the order of two weeks and may or may not indicate separate dinoflagellate populations.

Belle Glade
Fort Myers
Miami
Punta Gord
Tampa

graphic s
at surrou
confirm t
the disco
coast.

On the
tides requ
this does
red tides.
requireme
in any ne
quiremen
will be m

The po
has been
of fish m
that *Pror*
sp. show
salinity o
found a s
Island So
from Rile
33‰ in t
salinity of

These
some dinc
Mexico st
growth an
and vitam
(personal
these com
and Setlov

The exc
outbreak
hypothesis
phosphate
may be th

TABLE I(b). MEAN RAINFALL (inches) BY MONTHS AT FIVE FLORIDA WEATHER STATIONS

	J	F	M	A	M	J	J	A	S	O	N	D	Years
Belle Glade	1.68	1.48	2.70	2.33	3.60	9.01	6.90	8.06	7.41	4.84	2.90	1.32	1924–1951
Fort Myers	1.76	2.02	1.89	1.89	4.13	8.91	8.16	8.82	7.45	4.48	1.33	1.56	1851–1951
Miami	2.27	2.03	2.63	3.41	7.15	7.07	5.60	5.88	8.65	7.74	3.26	1.98	1855–1951
Punta Gorda	2.24	1.83	2.21	2.20	3.61	7.48	7.54	8.05	8.22	3.97	1.56	1.85	1914–1951
Tampa	2.69	2.56	2.33	2.01	2.99	7.25	7.95	8.18	6.42	3.19	1.72	2.07	1840–1951

graphic station in the discolored water (33.4‰) was lower than that at surrounding stations (34.99, 35.47, 36.17). This would seem to confirm the theory in so far as protista in general are concerned, since the discolored water was approximately 90 miles from the nearest coast.

On the basis of this evidence it can be stated tentatively that red tides require a discrete mass of water of relatively low salinity, but this does not imply that salinity difference is the sole requirement for red tides. The water mass must also satisfy the other physiological requirements of dinoflagellates. It does seem likely, however, that in any newly isolated mass of sea water the nutrient and other requirements of at least one of the algal or protozoan species in the mass will be met and will result in a temporary bloom.

The possible connection between heavy rainfall and fish mortality has been noted by Aggasiz (1890) and by Webb (1886) in their studies of fish mortality on the Florida Coast. Braarud (1951) has found that *Prorocentrum micans*, *Peridinium trochoideum* and *Amphidinium* sp. show maximal reproductive rate at 15–20 ‰ salinity. The salinity optimum for *Exuviaella baltica* is 10 ‰. In July 1952, Riley found a salinity of 24.9–22.7 ‰ in a bloom of *Gonyaulax* sp. in Long Island Sound off New Haven, Connecticut (personal communication from Riley). Ketchum and Keen (1948) have reported a salinity of 33‰ in the 1947 Gulf of Mexico outbreak, which is well below the salinity of normal Gulf of Mexico water (36 ‰).

These reports indicate that the salinity requirements of at least some dinoflagellates are such that a mass of water in the Gulf of Mexico stabilized by low salinity will be physiologically suitable for growth and reproduction. There is some indication that amino acids and vitamins are part of the nutritional requirements of dinoflagellates (personal communication from Provasoli). The possible presence of these compounds in fresh water is indicated by the work of Hutchinson and Setlow (1946).

The excessively high values of total phosphate found in the 1947 outbreak on the Florida Coast can be adequately explained on the hypothesis of Ketchum and Keen (1948), who stated that the excess phosphate "may be the result of terrigenous contamination . . . or may be the result of active swarming of organisms." Both of these

1953]
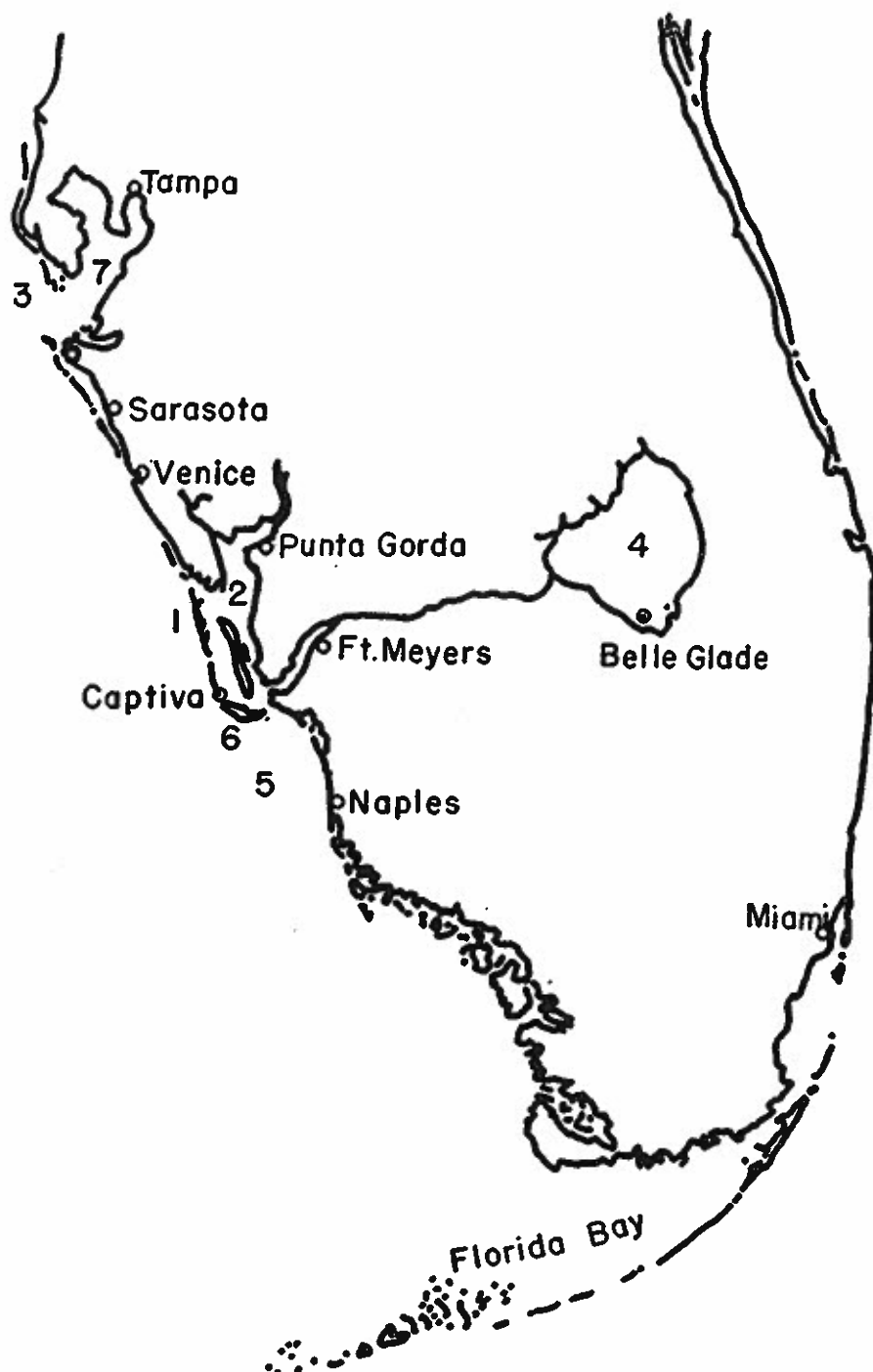
Figure 1. MAP OF SOUTHERN FLORIDA, SHOWING LOCATIONS MENTIONED
IN TEXT. 1. Boca Grande, 2. Charlotte Harbor, 3. Egmont Key, 4. Lake Okeechobee,
5. San Carlos Bay, 6. Sanibel Island, 7. Tampa Bay.

alternati
break of
August
(Table I
and Bana
as close a
a vertica
the organ
 Conclu
initiated
salinity
Florida C
can be ex
Upwelling
tions. O
satisfied,
the physi
depend or
Preventio
pattern o

REFERENCES

AGASSIZ, ALEXANDER

1890. Note on Shaler, 1890. Bull. Mus. comp. Zool. Harv., *16:* 157–158.

ANONYMOUS

1882. Article in Sunland Tribune, Tampa, Florida. Bull. U. S. Fish Comm., *2:* 104.

BRAARUD, TRYGVE

1951. Salinity as an ecological factor in marine phytoplankton. Physiol. Plant., *4:* 28–34.

BRONGERSMA-SANDERS, M.

1948. The importance of upwelling water to vertebrate paleontology and oil geology. Verh. Akad. Wet. Amst., Afd. Natuurkunde, Tweedie Sect., *45* (4): 112 pp.

Davis, C. C.

1947. *Gymnodinium brevis* n. sp., a cause of discolored water and animal mortality in the Gulf of Mexico. Bot. Gaz., *109:* 358–360.

GALTSOFF, P. S.

1948. Red tide. Spec. Sci. Rep. U. S. Fish and Wildl. Serv., No. 46: 44 pp.

GUNTER, G., R. H. WILLIAMS, C. C. DAVIS AND F. G. W. SMITH

1948. Catastrophic mass mortality of marine animals and coincident phytoplankton bloom on the west coast of Florida, November 1946 to August 1947. Ecol. Monogr., *18:* 309–324.

GLENNAN, A. H.

1886. Fish killed by poisonous water. Bull. U. S. Fish Comm., *6:* 10–11.

HOWELL, J.

1953. *Gonyaulax monilata*, sp. nov., the causative dinoflagellate of a red tide on the east coast of Florida in August-September, 1951. Trans. Amer. micr. Soc. (in press).

HUTCHINSON, G. E. AND JANE SETLOW

1946. Limnological studies in Connecticut. VIII. The niacin cycle in a small inland lake. Ecology, *27:* 13–22.

ICHIE, T. AND T. KATSUMI

1949. On the report of observations of the hydrographical conditions in the Osaka Wan after the heavy rain caused by the typhoon "Della." Pap. Rep. in Oceanography, Kobe Marine Observ., No. 3.

INGERSOLL, E.

1882. On the fish mortality in the Gulf of Mexico. Proc. U. S. nat. Mus., *4:* 74–80.

JEFFERSON, J. P., J. PORTER AND T. MOORE

1878. On the destruction of fish in the vicinity of the Tortugas during the months of September and October, 1878. Proc. U. S. nat. Mus., *1:* 244–245.

KETCHUM, B. H. AND JEAN KEEN

1948. Unusual phosphorus concentrations in the Florida "red tide" sea water. J. mar. Res., *7:* 17–21.

KIERSTEAD, HENRY AND L. B. SLOBODKIN

1953. The size of water masses containing plankton blooms. J. mar. Res., *12* (1): 141–147.

KUDO, R. R.

1947. Protozoology.

RILEY, G. A.

1951. Parameters of t

SMITH, F. G. W.

1941. Sponge disease i
Ecology, *22:* 41ξ

TAYLOR, H. F.

1917. Mortality of fis
(1917). Append

WALKER, S. T.

1884. Fish mortality iı

WEBB, J. G.

1886. The mortality oɩ
11–13.

KUDO, R. R.
   1947.   Protozoology.   3rd ed., Charles C. Thomas, Springfield, Illinois.   778 pp.
RILEY, G. A.
   1951.   Parameters of turbulence in the sea.   J. mar. Res., *10*: 247–256.
SMITH, F. G. W.
   1941.   Sponge disease in British Honduras and its transmission by water currents. Ecology, *22*: 415–421.
TAYLOR, H. F.
   1917.   Mortality of fishes on the west coast of Florida.   Rep. Comm. Fish. (1917).   Append. 3, 24 pp.
WALKER, S. T.
   1884.   Fish mortality in the Gulf of Mexico.   Proc. U. S. nat. Mus., *6*: 105–109.
WEBB, J. G.
   1886.   The mortality of fish in the Gulf of Mexico.   Bull. U. S. Fish Comm., *6*: 11–13.